A Multivariable Laguerre-Based Indirect Adaptive Predictive Controller Applied To A Fuel Blending

M. Huzmezan and G. A. Dumont
Department of Electrical and Computer Engineering
University of British Columbia,Vancouver, B.C. Canada

W.A. Gough, T. Janiewicz, S. Kovac and D. Meade
Universal Dynamics Technologies Inc.

Outline

1. Defining and motivating the problem

2. Commercial adaptive controller ingredients:
   MIMO Laguerre based identification
   Predictive Control

3. Implementation issues

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5. Rewarding results

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7. A few statements about adaptive control commercial products

Definitions and motivation

- Process industries need a multivariable predictive controller that:

  1. has low cost
  2. is easy to setup
  3. maintains an adaptive behavior [1] (accounting for plant non-linearities and potential mismodeling).

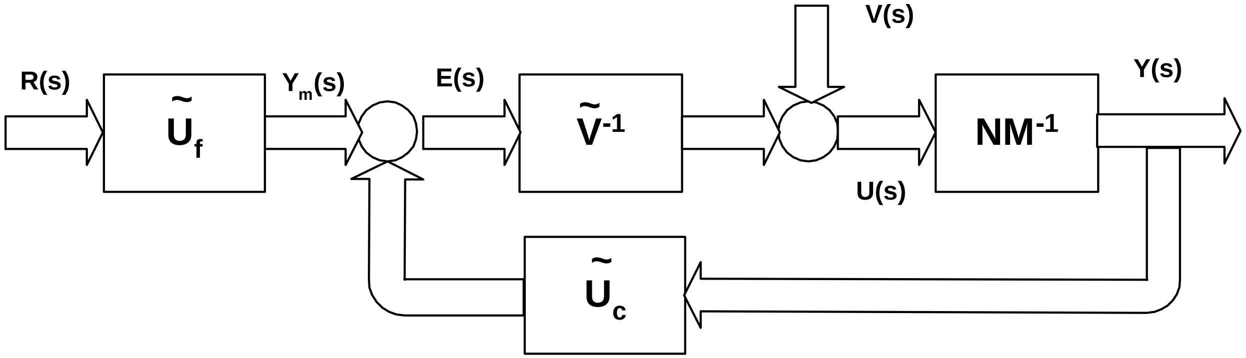
- In answer an indirect adaptive predictive controller Brainwave Multimax is proposed

- To evaluate its performance the control of a fuel blending process is presented

[1] "To adapt = To adjust oneself to particular conditions, in harmony with a particular environment" (Webster)
"A controller is adaptive if it is based on a posteriori information" (Zames)

Multivariable Adaptive Control

- Probably the most general framework in which multivariable adaptive control can be understood involves using normalized coprime factors and the Bezout Identity:



- Typical closed loop equations:

$$\begin{aligned} Y(s) &= N(s)M^{-1}(s) && (1)\\ Y_m(s) &= \tilde{U}_f(s)R(s) = N_m(s)M_m^{-1}(s)R(s) && (2)\\ E(s) &= Y_m(s) - \tilde{U}_c(s)Y(s) && (3)\\ U(s) &= \tilde{V}^{-1}(s)E(s) + V(s) && (4) \end{aligned}$$

Equations clarifying the concept (I)

- The controller: $C(s) = \tilde{V}^{-1}\tilde{U}_c$
- The Plant/Controller Bezout identity: $\tilde{V}(s)M(s) + \tilde{U}_c(s)N(s) = I$.
- If above factorization exists is equivalent to $C(s)$ being a stabilizing controller for $P(s)$
- Closed loop dependencies for $V(s) = 0$:

$$Y(s) = NM^{-1}(I + \tilde{V}^{-1}\tilde{U}_c NM^{-1})^{-1}\tilde{V}^{-1}\tilde{U}_f R(s) \tag{5}$$

- Based on the Bezout identity we can simplify:

$$NM^{-1}(I + \tilde{V}^{-1}\tilde{U}_c NM^{-1})^{-1}\tilde{V}^{-1} = N(\tilde{V}M + \tilde{U}_c N)^{-1} = N \tag{6}$$

- In conclusions: $Y(s) = NU_f R(s)$ and since $(I - \tilde{U}cN) = \tilde{V}M$ the error is $E(s) = \tilde{V}M\tilde{U}_f R(s)$ and the command can be computed as $U(s) = MU_f R(s)$.

Equations clarifying the concept (II)

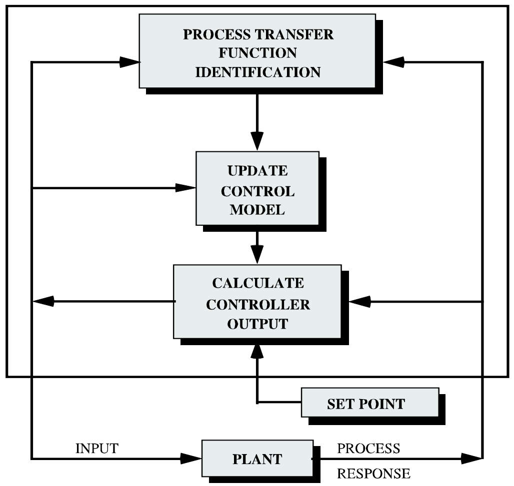
- Now assuming: $R(s) = 0$:

$$
\begin{aligned}
Y(s) &= NM^{-1}(I + \tilde{V}^{-1}\tilde{U}_c NM^{-1})^{-1}V(s) && (7)\\
&= N(M + \tilde{V}^{-1}\tilde{U}_c N)^{-1}V(s) && (8)\\
&= N(\tilde{V}M + \tilde{U}_c N)^{-1}\tilde{V}^{-1}V(s) && (9)\\
&= \tilde{N}\tilde{V}^{-1}V(s) && (10)
\end{aligned}
$$

- Now applying the superposition principle:

$$
\begin{aligned}
Y(s) &= N\tilde{U}_f R(s) + N\tilde{V}^{-1}V(s)\\
U(s) &= M\tilde{U}_f R(s) + M\tilde{V}^{-1}V(s) && (11)
\end{aligned}
$$

Indirect Adaptive Control



- The MIMO indirect adaptive controller takes involves two steps:
  1. plant NM^{-1} identification
  2. obtaining a solution $\tilde{V}^{-1}\tilde{U}_c$ of the Bezout identity
- To achieve this a wide variety of identification and controller design methodologies can be used
- Our choice is **MIMO Laguerre based identification** and **Model Predictive Control**

Identification of Laguerre Models (I)

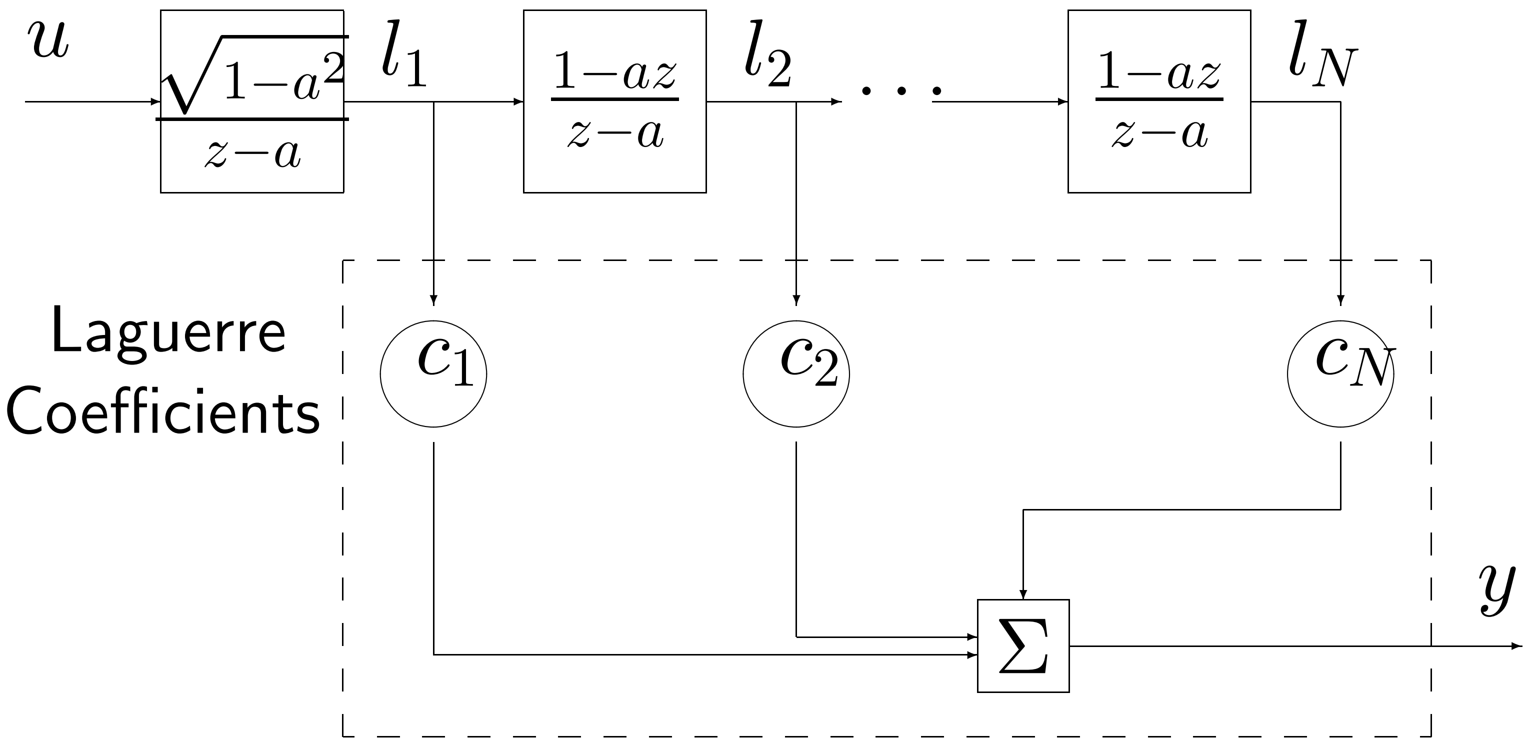
Consider the real plant described by

$$y(t) = \sum_{i=1}^{N} c_i L_i(q) + \sum_{i=N+1}^{\infty} c_i L_i(q) + w(t)$$

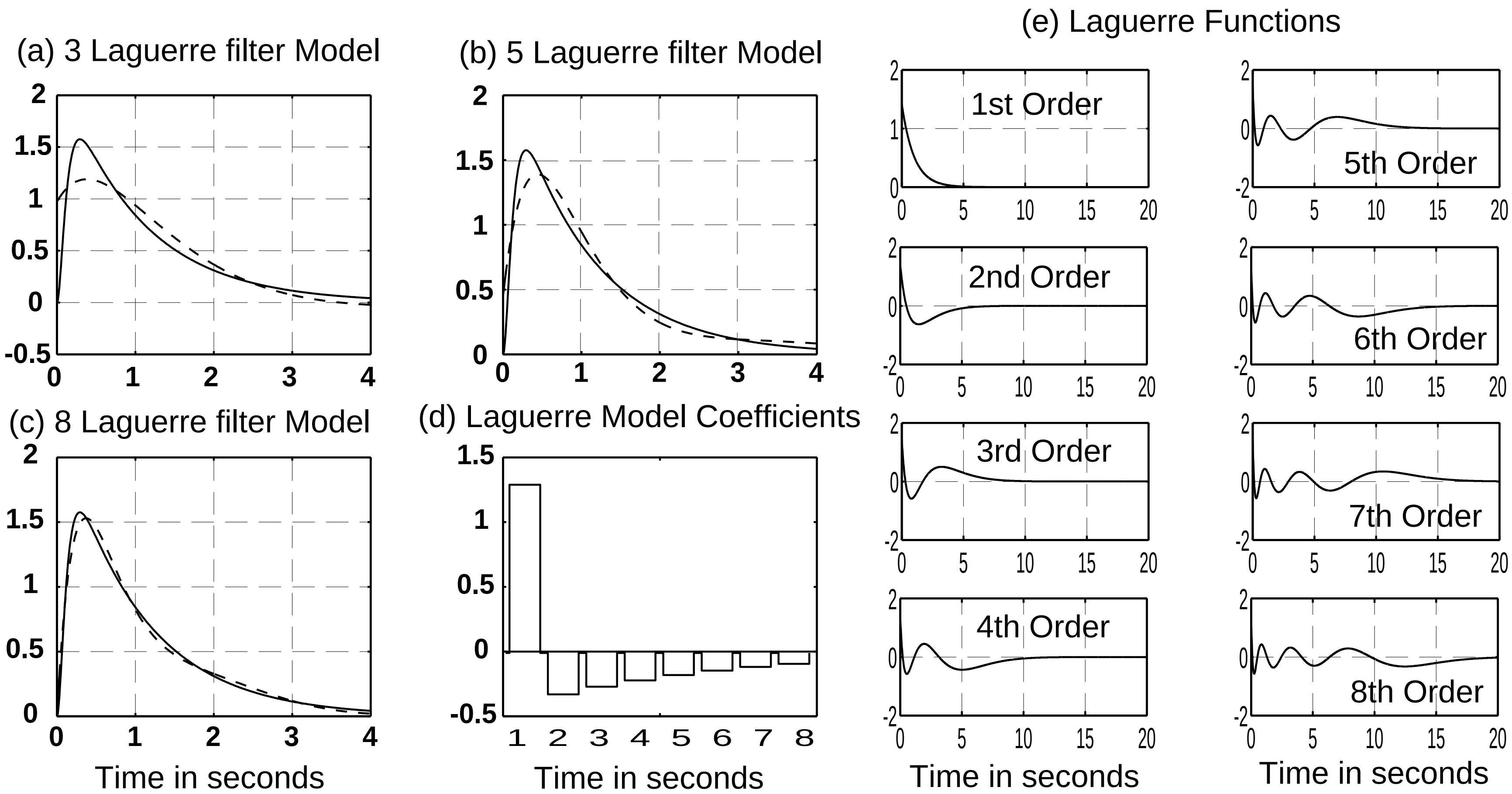
where $w(t)$ is a disturbance.
This model has an output-error structure, is linear in the parameters, and gives a convex identification problem.

- Even if $w(t)$ it colored and non-zero mean, simple least-squares provide consistent estimates of the c_i's.
- The estimate of the nominal plant, i.e. of c_i, for $i = 1, \cdots, N$ is unaffected by the presence of the unmodelled dynamics represented by c_i, for $i = N+1, \cdots, \infty$.

Identification using a bank of Discrete Laguerre Functions (II)



Example of Laguerre Modelling



The identification engine: Recursive Least Squares

- A modified RLS - the exponential Forgetting and Resetting Algorithm (EFRA)(Goodwin et al.) - allows tracking of time-varying parameters while guaranteeing boundedness of covariance matrix:

$$
\begin{aligned}
\varepsilon(t+1) &= y(t+1) - x^T(t+1)\hat{\theta}(t) \\
\hat{\theta}(t+1) &= \hat{\theta}^T(t) + \frac{\alpha P(t) x(t+1)}{\lambda + x^T(t+1) P(t) x(k+1)} \varepsilon(t) \\
P(t+1) &= \frac{1}{\lambda}\left[P(t) - \frac{P(t) x(t+1) x^T(t+1) P(t)}{\lambda + x(t+1)^T P(t) x(t+1)} \right] + \beta I - \gamma P(t)^2
\end{aligned}
$$

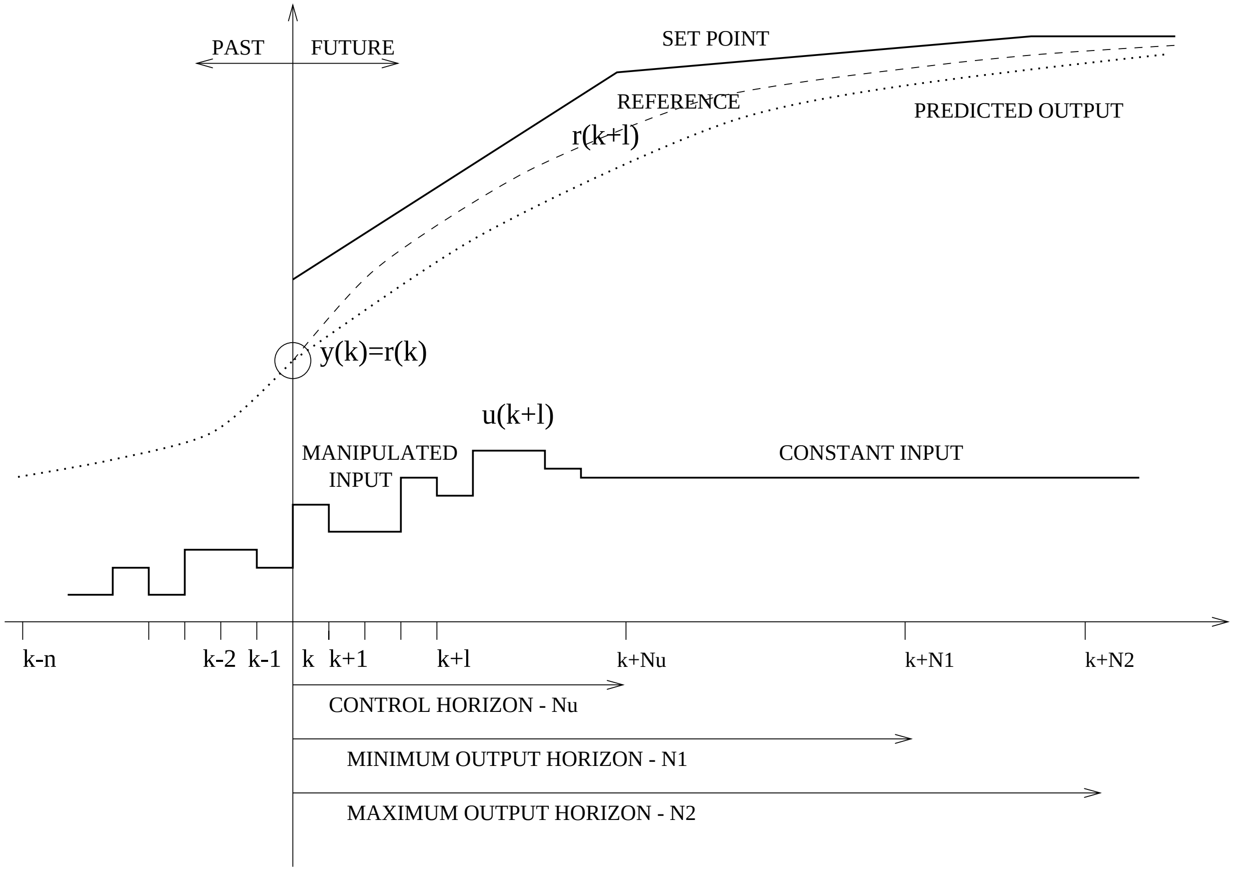
  I is the identity matrix, and α, β and γ are constants.

- With $\alpha = 0.5$, $\beta = \gamma = 0.005$ and $\lambda = 0.95$, $\sigma_{min} = 0.01$ and $\sigma_{max} = 10$.

Identification in Closed Loop

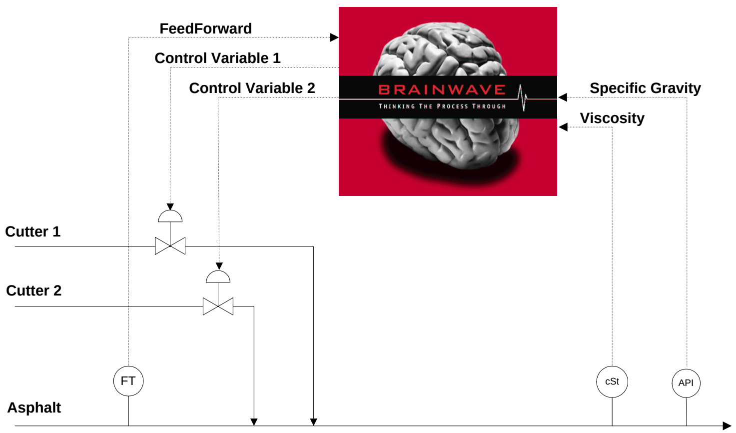
- For closed loop identification, the identifiability of the process may be problematic.
- There are ways employed in the controller to guarantee closed-loop identifiability:
  1. A sufficiently exciting signal independent of y is injected into the loop either at setpoint or at the control input.
  2. Switching, as modelling reveals new dynamics, between different regulators.
- The latter situation is favorable for the adaptive control situation since the controller is continously changing.
- There are also subtle interactions between identification and control in a closed-loop situation that affect the frequency distribution of the estimation variance and bias.
- It can be shown that when identification has to be performed under an output variance constraint, then a closed-loop experiment is optimal.

The Model Predictive Control algorithm employed



Briefing on the fuel blending process (I)

- A by-product of crude oil refining process is asphalt, which can be turned into a low cost fuel for ships and is also used for road construction.
- The process of transforming the asphalt into a low cost fuel requires blending the asphalt with cutting agents to meet both specific gravity and viscosity specifications which are making the asphalt transportable.
- The fuel cutters are expensive and hence the need to minimize the cost of the cutters while maintaining the specific gravity and viscosity of the blended fuel is mandatory.



Briefing on the fuel blending process (II)

- The MIMO plant has two inputs (two different cutter types) and two outputs (specific gravity and viscosity) and a measured disturbance (the flow of asphalt).
- The plant model presented large discrepancies between channels, different dynamics including different gains, time delay and strong cross-coupling.
- The fuel blending control loop had a time constant of 60 seconds and a dead time of 4 minutes.
- The blending of the cutter with the asphalt occurred when the asphalt temperature was 525F.
- The blended mixture then travels through a series of heat exchangers and the specific gravity is measured when the final mixture is 75F.
- The specific gravity must be maintained at 12.3 API (American Petroleum Institute specific gravity units) and the addition of the cutting medium must be minimized.
- The viscosity control loop presented similar dynamics with a negative gain.

Rewarding results[2]

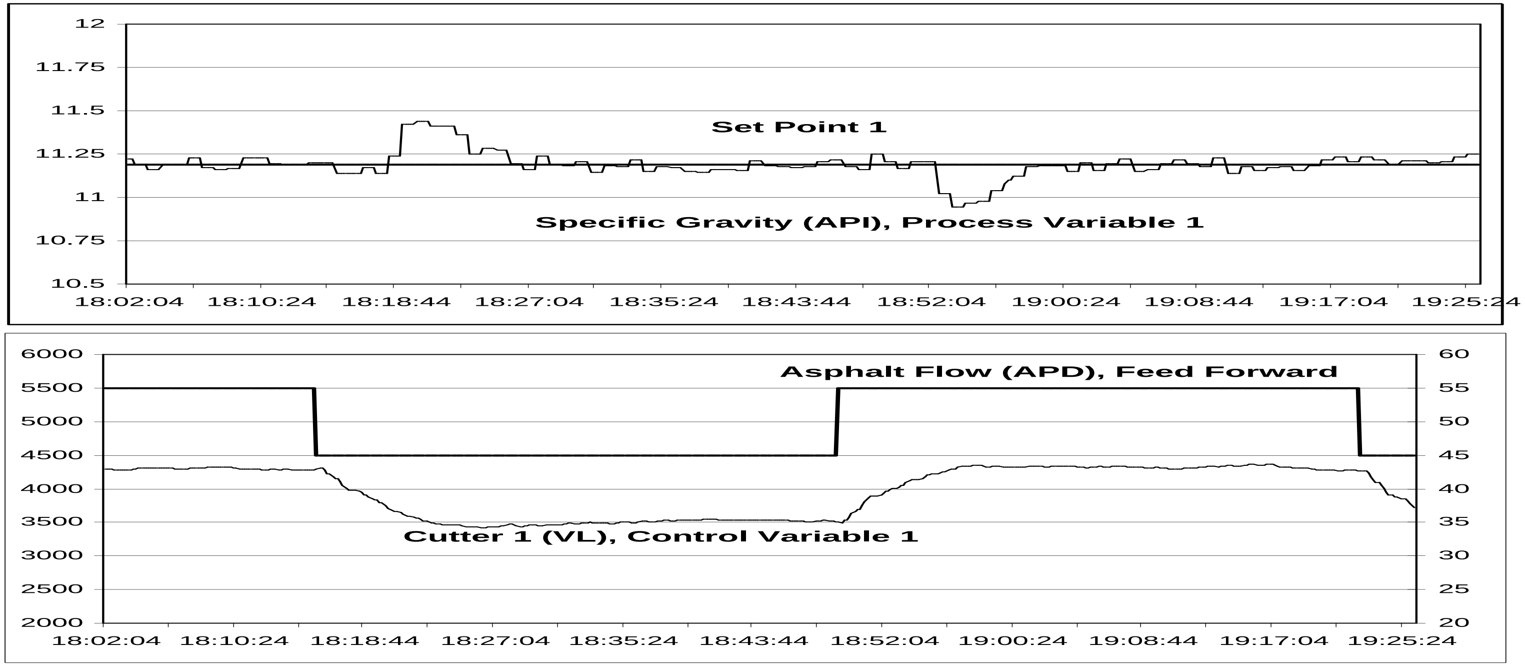


Figure 1: The closed loop control of specific gravity

[2]For commercial reasons data presented reflects, up to a simulation model, the reality found in the refinery.

Rewarding results[3]

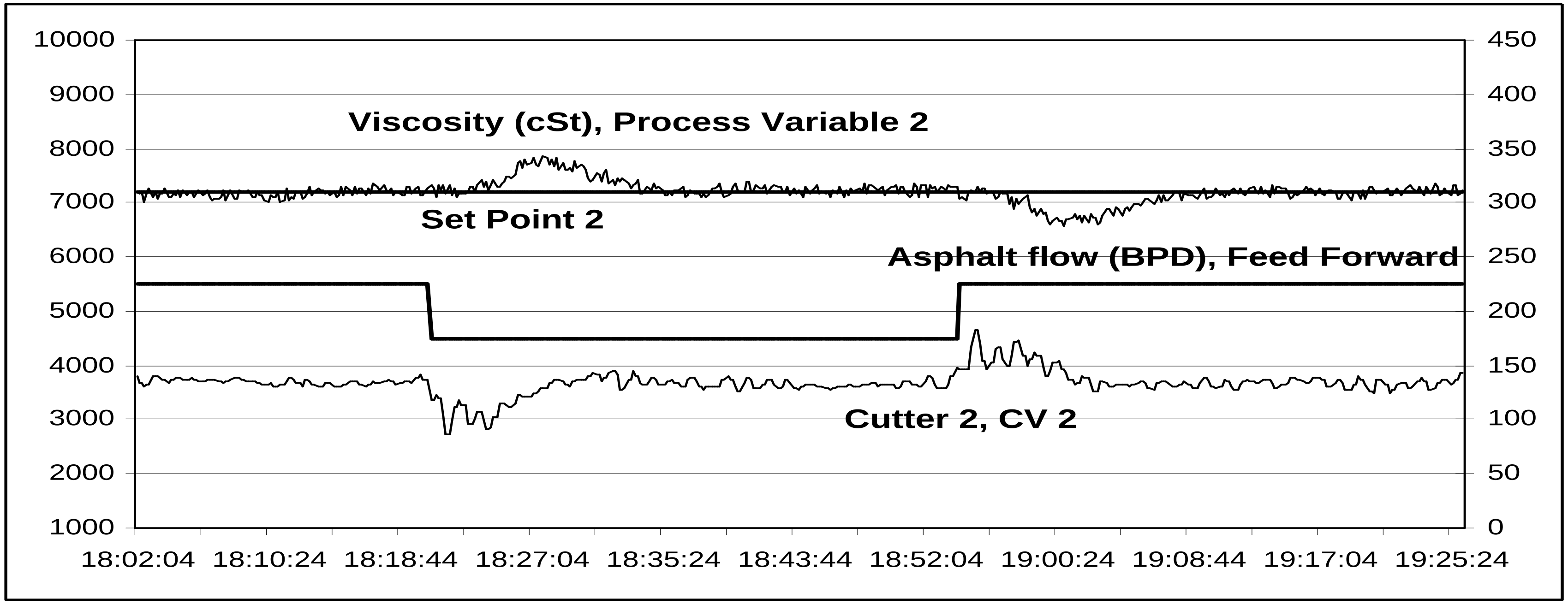


Figure 2: The closed loop control of fuel viscosity

[3]The results exceeded the existing control performance by several orders of magnitude outperforming at the same time the manual control capabilities of the operators.

Implementation details

- BrainWave MultiMax was interfaced to a Siemens Moore Apacs System through a Modbus connection.
- Once the adaptive controller was integrated into the control strategy, bump tests were initiated to determine the models for the process response.
- A startup multi-model approach was utilized to take into account the effect different cutters would have on the blended mixture.
- The process of bump tests, model identification and control optimization took three days.

A glance at the user interface

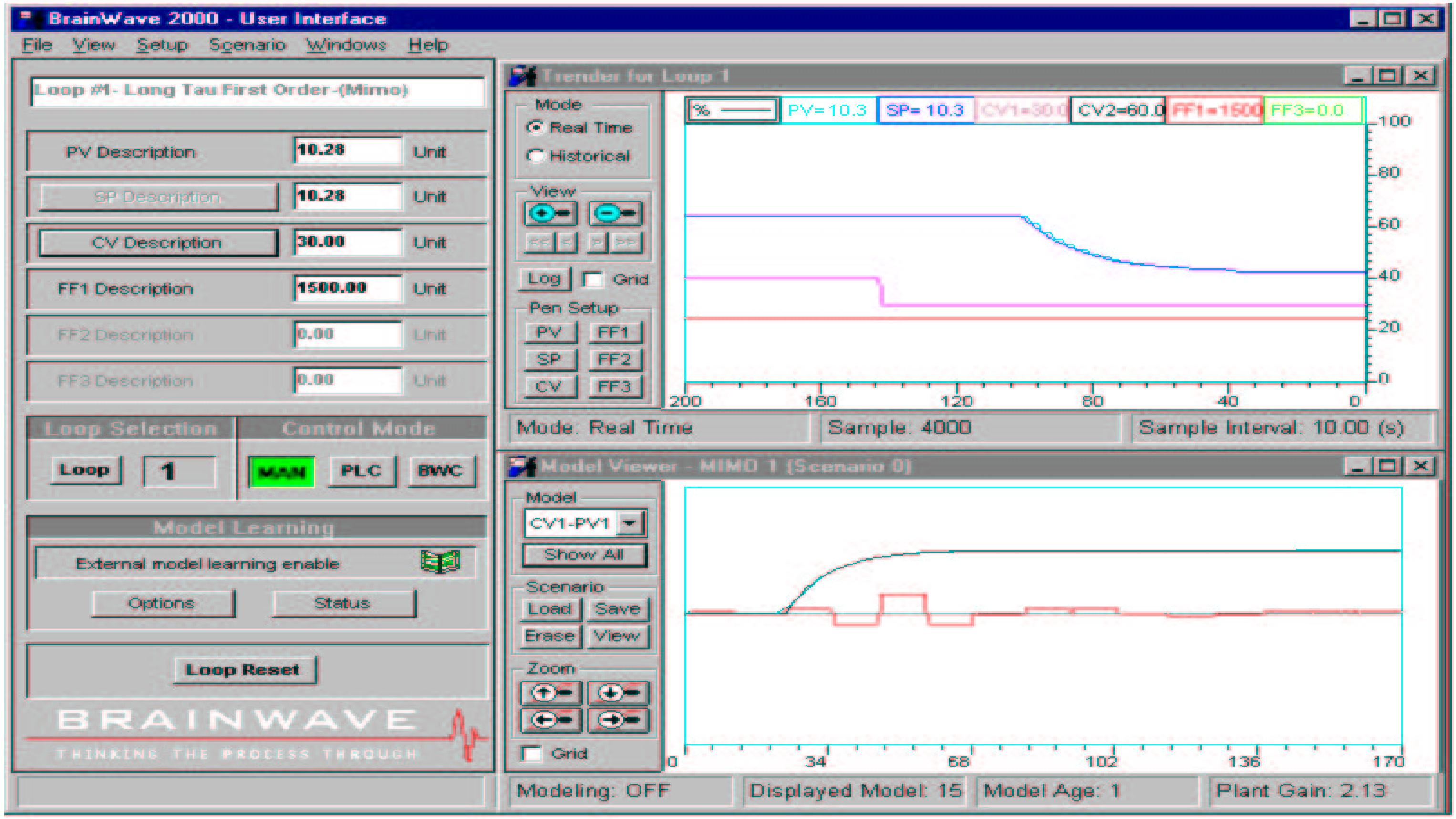


Figure 3: The controller face plate reflecting the trender, model viewer and controller

Controller related conclusions

- BrainWave MultiMax was developed for use on multi-input/multi-output MIMO processes with possible integrating responses, exhibiting long delays and time constants.
- The controller was developed and tested using a flexible Matlab Simulink test-bed.
- A thorough analysis of the parameters involved in the controller provided golden rules for a number of tuning parameters, dramatically reducing the commissioning time.
- Particular attention was paid to the development of the graphic user interface (GUI)
- The real time implementation achieves sample times as low as 0.1 [s] for a medium size 6X6 with 3 measured disturbances per loop MIMO systems.
- The applicability of this controller ranges from pulp and paper to biomedical engineering.
- The main benefits of this control strategy are: i) a systematic tuning procedure; ii) reduced cross-couplings between channels and iii) minimized closed-loop overshoot and settling time.

Application related conclusions

- Reduced cutter addition is saving an estimated $ 150,000 dollars annually, with a return on investment of less than 2 months.
- The possibility for the operators to redirect their attention to more critical loops is greatly appreciated.
- BrainWave MultiMax was implemented quickly and is easily modified by the company process engineers.

Commercial Controllers Are Embracing More And More Adaptive Control Ideas

- Adaptive control has a relatively long history and a rich collection of algorithms is available but only few are providing reliable industrial solutions
- Prohibitive costs of predictive control and a low number of commercially available multivariable adaptive controllers prevent industries that operate on small profit margins to take advantage of such technology.
- This is a list of currently available tools:
  - BCI Autopilot www.bciautopilot.com
  - Brainwave www.brainwave.com
  - Connoiseur & Exact www.foxboro.com
  - CyboCon www.cybocon.com
  - Intune www.controlsoftinc.com
  - Knowledgescape www.kscape.com
  - QuickStudy www.adaptiveresources.com
- **With careful engineering, adaptive control can provide significant benefits**